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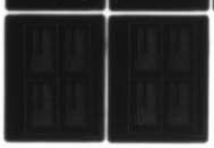

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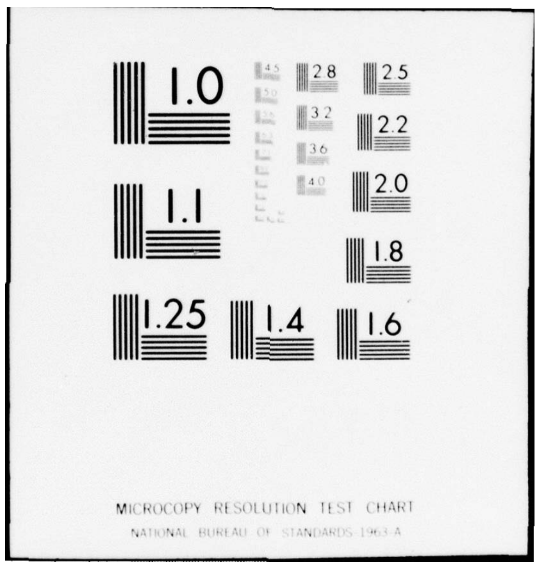
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MR 77-1

A Positive Displacement Oscillatory Water Tunnel

by

Karl E.B. Lofquist

MISCELLANEOUS REPORT NO. 77-1
FEBRUARY 1977

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Prepared for

U.S. ARMY, CORPS OF ENGINEERS

COASTAL ENGINEERING RESEARCH CENTER

Kingman Building

Fort Belvoir, Va. 22060

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER MR-77-1	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A POSITIVE DISPLACEMENT OSCILLATORY WATER TUNNEL		5. TYPE OF REPORT & PERIOD COVERED Miscellaneous Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Karl E.B. Lofquist		8. CONTRACT OR GRANT NUMBER(s) CERC Agreement No. 76-30
9. PERFORMING ORGANIZATION NAME AND ADDRESS National Bureau of Standards Mechanics Division Washington, D.C. 20234		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D31193
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Army Coastal Engineering Research Center (CERRE-CP) Kingman Building, Fort Belvoir, VA 22060		12. REPORT DATE February 1977
		13. NUMBER OF PAGES 26 28p.
14. MONITORING AGENCY NAME & ADDRESS (If different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Coastal processes	Sand transport
Permeability effects	Water tunnel
Prototype tests	Waves

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The water tunnel described produces sinusoidal flow with peak velocities adjustable from 0 to at least 30 centimeters per second for any period between 3 and 25 seconds. The tunnel is of U-tube design with the middle horizontal part comprising the test section. The vertical end parts are two cylinders with tight-fitting pistons at one end, and two reservoirs open to air at the other. The pistons are driven by a variable-speed electric motor, with an adjustable counterweight permitting operation at resonance at any period.

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PREFACE

This report is published to document the design, construction, and operation of an oscillatory water tunnel. The test section of this facility replicates prototype conditions at the seabed under sinusoidal waves offshore of the breaker zone. The water tunnel, constructed in the Fluid Mechanics Building of the National Bureau of Standards (NBS), Gaithersburg, Maryland, has performed satisfactorily for over 2 years in studies of sand movement and transport. The work was carried out under the coastal processes program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Karl E.B. Lofquist, Physicist, Fluid Mechanics Section, Mechanics Division, NBS, under CERC Agreement No. 76-30. Previous CERC Agreements Nos. 70-99 and 73-25 supported construction of the water tunnel. The author especially thanks Louis Lembeck who shared the work of constructing the tunnel.

Drs. M.M. Das and R.J. Hallermeier, Coastal Processes Branch, were the CERC monitors for the agreements, under the general supervision of Dr. C.J. Galvin, Jr., Chief, Coastal Processes Branch, Research Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

John H. Cousins

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.8532	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

A	cross-sectional area of flow over sand bed
A_c	combined cross-sectional area of cylinders
A_r	combined cross-sectional area of reservoirs
$A(\ell)$	cross-sectional area of flow, a function of ℓ
E	total energy
g	acceleration due to gravity
K_v	time variable part of the kinetic energy
L	length of test section
ℓ	distance along the flow path (see Fig. 3)
ℓ_o	total flow path length when $s = o$
M_a	mass of active counterweight
M_p	mass of passive counterweight
P_v	time variable part of the potential energy
S	amplitude of piston motion (half stroke)
S_m	maximum amplitude of piston motion (maximum half stroke)
s	displacement of pistons from zero level
s_r	displacement of free surface in reservoirs from zero level
T	period of oscillation
T_o	resonance period when $y = o$
t	time
U	amplitude of flow velocity in test section
v	magnitude of the velocity vector
$\overline{v}(\ell)$	average velocity over a cross section, a function of ℓ
y	elevation of the active counterweight when $s = o$

y_m maximum possible value of y

z vertical elevation

α shape factor (eq. 7)

β shape factor (eq. 11)

ρ density of water

σ frequency of oscillation, $2\pi/T$

σ_o resonance frequency when y = o, $2\pi/T_o$

A POSITIVE DISPLACEMENT OSCILLATORY WATER TUNNEL

by

Karl E.B. Lofquist

I. INTRODUCTION

This report describes a general purpose oscillatory water tunnel able to provide purely sinusoidal motion over wide ranges of period and amplitude. The tunnel was designed to study, under near prototype conditions, the effects of bed permeability upon the net movement of sand by offshore wave action. Lofquist (1975) described the unique features of the tunnel special to the study of permeability effects. Subsequent removal of those special features and doubling the depth of flow in the test section have produced the general purpose tunnel described here. This tunnel has no single capability or capacity not found in other existing tunnels (discussed in Section VII). However, the capabilities it does have combined with its modest size and power requirement make this tunnel unusual.

II. GENERAL DESIGN

The water tunnel is of U-tube design with the middle horizontal part comprising the test section (Figs. 1 and 2). The vertical end parts of the tunnel are two cylinders with tight-fitting pistons at one end, and two reservoirs open to the air at the other. The pistons, in unison, move the water over the sand bed between the cylinders and reservoirs. The cylinders and reservoirs were designed in pairs to provide two separate channels when the test section was divided longitudinally by a partition. With the partition removed, the cylinders and reservoirs act as units.

A variable-speed motor (Reeves 3/4 horsepower) drives the two pistons in unison by a combination of sprockets and a worm gear that rotates two arms at opposite ends of a common axis. Ball-bearing "pins" attached to the arms at an adjustable distance from the axis move in parallel circles and slide in horizontal slots in a frame constrained to move vertically. The pistons are attached to the upper part of the frame. A constant rate of rotation of the arms drives the frame, or "scotch yoke", and the attached pistons in simple harmonic motion. The yoke and pistons are balanced by a "passive" counterweight.

The required power input has been minimized and a nearly steady operation at any period of rotation has been made possible by the addition of an "active" counterweight. This weight is supported by a frame that rotates at twice the rate of the arms which drive the yoke and pistons. The displacement of the weight from the axis of its supporting frame affects the resonance period (neglecting friction) of the entire system. By adjusting the position of the weight (this can be

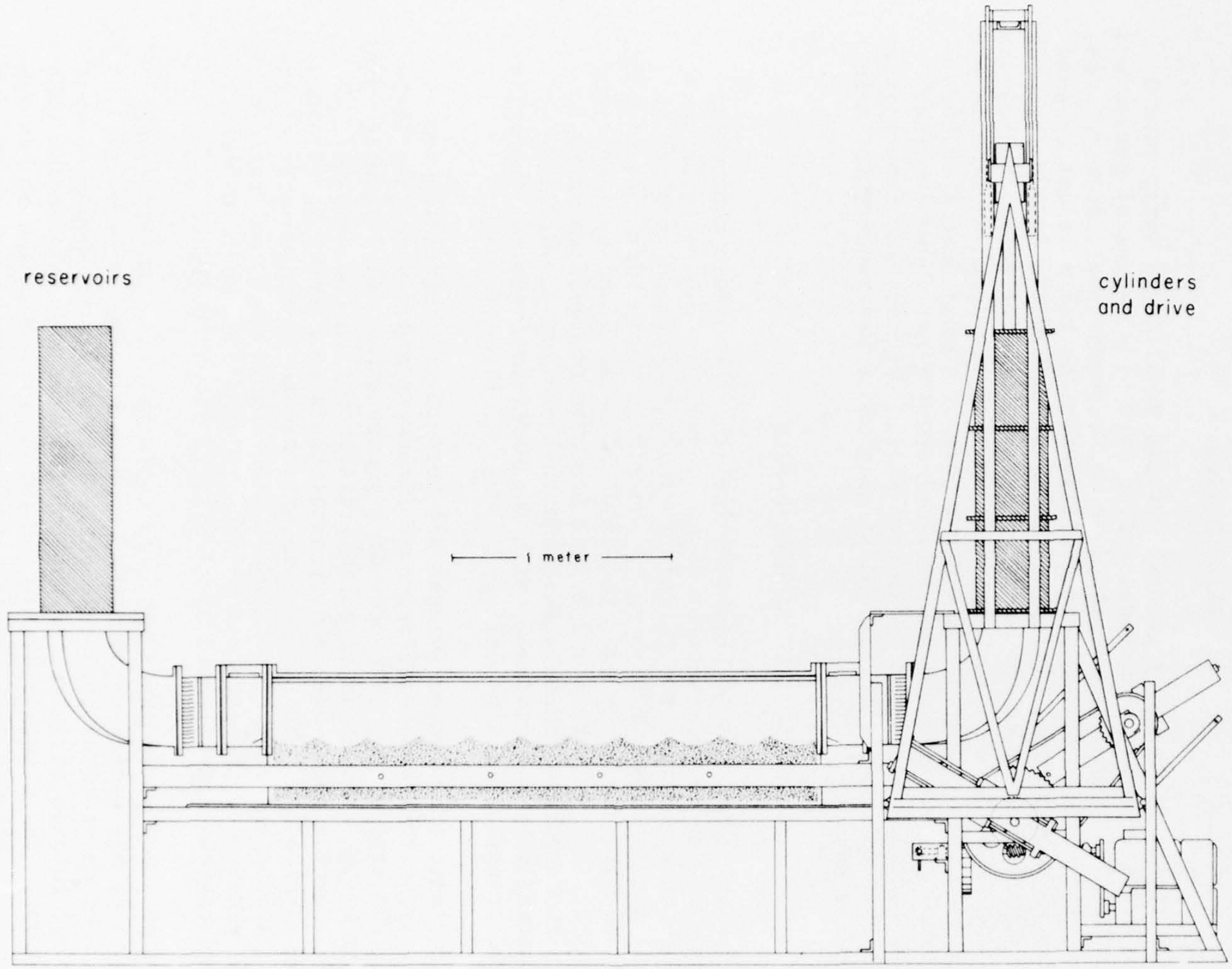

Figure 1. Drawing of the oscillatory water tunnel.

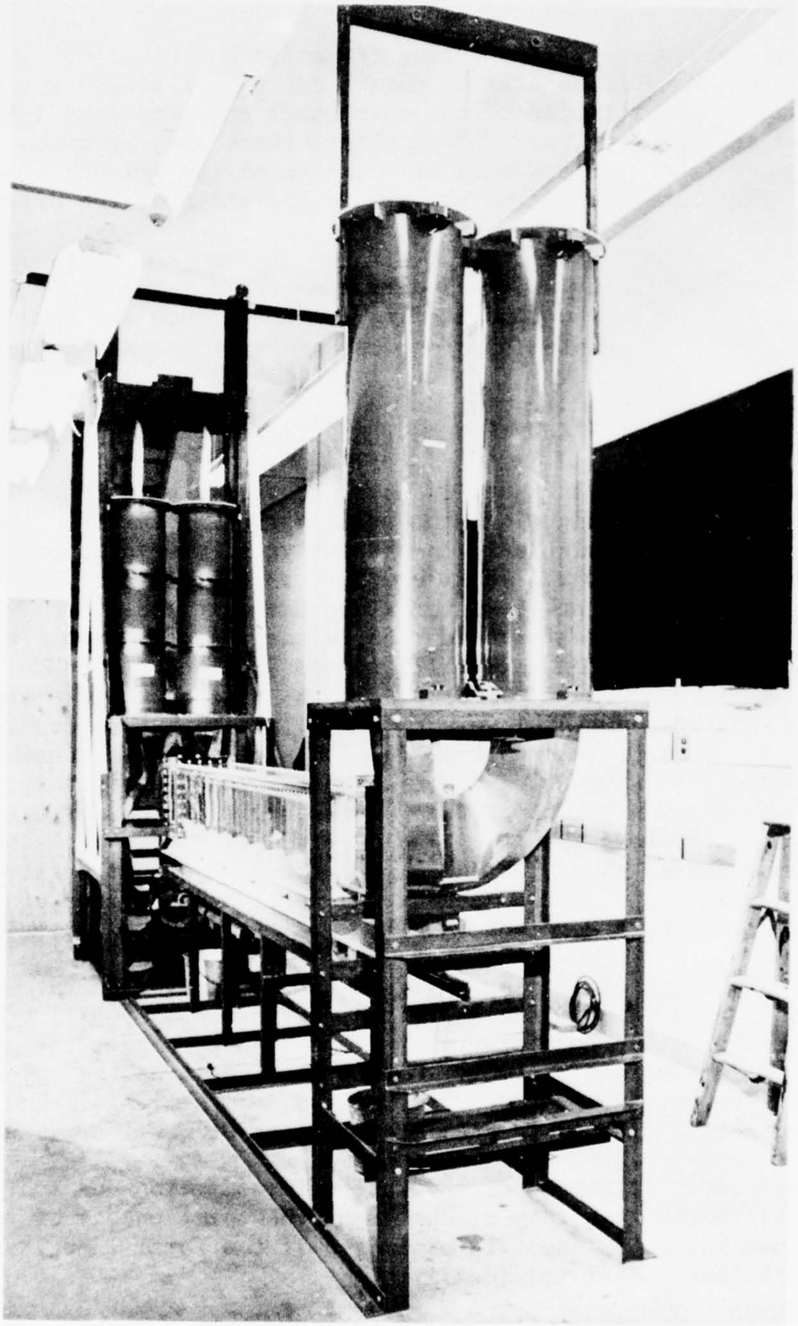

Figure 2. Photo of the tunnel from the reservoir end.

done while the weight is in motion) the tunnel can operate at resonance at any period. The theory and operation of the active counterweight system are discussed in Section III.

The drive system includes a timing mechanism which, at 45° intervals in the angle of the driving arms or phase, can time a single rotation of the worm shaft. One rotation of the worm shaft occupies only 1/48 of a cycle of the driving arms, or 7.5° of phase; therefore, separate timings provide a quasi-instantaneous rate of rotation of the driving arms as a function of phase and a check on the steady operation of the drive system.

The flow out of the cylinders and reservoirs is turned from vertical to horizontal by curved conduits and continues into the test section through horizontal removable "spools" with constant rectangular cross section.

III. COUNTERWEIGHT ANALYSIS

A schematic diagram in Figure 3 shows the tunnel with the cylinders and drive system at the right and the reservoirs at the left. The schematic is presented to assist only in the analysis; true proportions are provided in Figures 1 and 2. In Figure 3, ℓ is the distance from the zero position of the pistons measured along the centroid of the water conduit. Except in the test section and in the adjacent spools the conduit is divided and the centroid falls in the area between. The cross-sectional area of the conduit, including both branches where there are two, is denoted $A(\ell)$. Special values of $A(\ell)$ are: A_c, the combined cross-sectional area of the two cylinders; A, the cross-sectional area of the test section, without divider, above the sand bed; and A_r, the combined cross-sectional area of the two reservoirs which, by circumstance, is slightly less than A_c. The combined mass of the pistons and their yoke is denoted by M_p, which is also the mass of the passive counterweight (actually hung as two separate halves), and the mass of the active counterweight is denoted by M_a.

The purpose of the following analysis is, for any given rate of rotation σ, to determine y, the elevation (which can be positive or negative) of the active counterweight when $s = o$, such that the power input from the motor is a minimum. Under this condition the motor is required to work only against the dissipative forces of fluid and piston friction and not to lift or to accelerate masses of metal or water.

The power input in excess of the rate of dissipation due to friction is equal to the time rate of change of the total energy of the system. Thus, the power input is minimized if the total energy is held constant with time. That is, ideally,

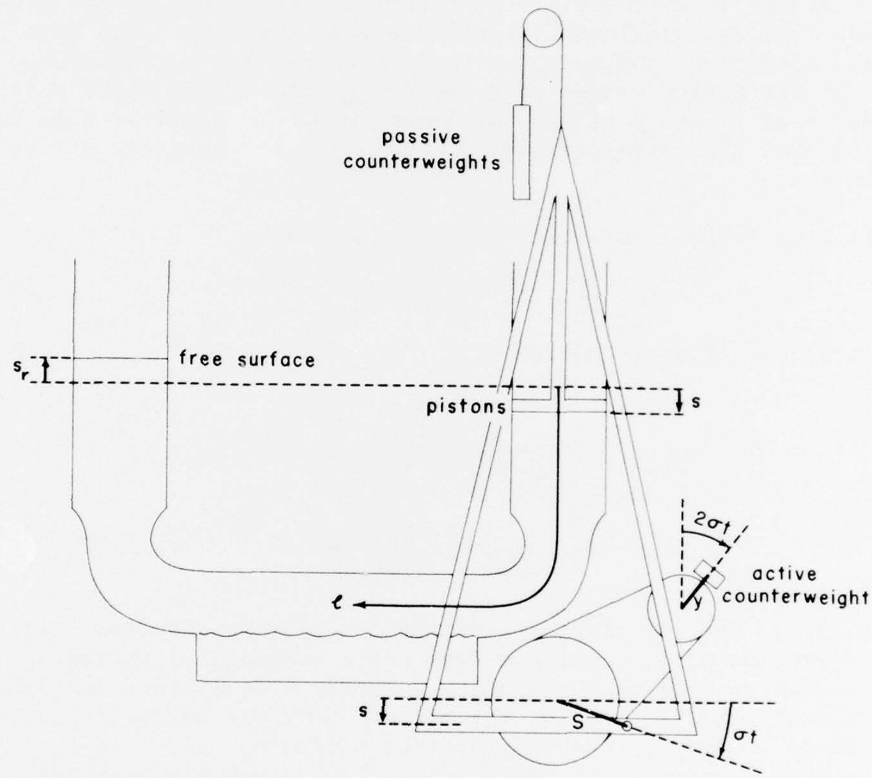

Figure 3. Schematic diagram of the tunnel and drive system defining quantities in the counterweight analysis.

$$\frac{\partial E}{\partial t} = 0 \quad , \tag{1}$$

where E is the sum of the potential and kinetic energies excluding thermal energy and the kinetic energy of turbulent eddies. The expression for E contains y which is then determined to satisfy equation (1). In the computations of potential and kinetic energies, any components which are constant with time, such as the potential energy of balanced weights or the kinetic energy of rotating parts, can be included in undetermined constants and therefore can be disregarded. The potential and kinetic energies are determined from the mass, elevation, and speed of solid members, and by the integrals over the entire volume of water of ρgz and $\rho v^2/2$, where ρ is the density of water, g is the acceleration due to gravity, z is the elevation over any convenient level, and v is the magnitude of the velocity vector.

Following Figure 3 all motions are governed by

$$s = S \sin \sigma t \quad , \tag{2}$$

and by the conditions of continuity:

$$s_r = \frac{A_c}{A_r} s \tag{3}$$

$$\overline{v}(\ell) = \frac{A_c}{A(\ell)} \frac{ds}{dt} \quad , \tag{4}$$

where s and s_r are the displacements of the pistons and free surface in the direction of increasing ℓ from their (common) elevation at t = 0, and where $\overline{v}(\ell)$ is the average velocity over a cross section in the direction of ℓ. Taking the elevation of the active counterweight to be y cos $2\sigma t$, and the variable potential energy of the water to be its potential energy at any time, minus its potential energy when s = 0, the total variable potential energy of the system is found to be:

$$P_v = M_a \, g \, y \cos 2\sigma t + \frac{\rho g A_c}{2} \left(1 + \frac{A_c}{A_r}\right) s^2 \quad . \tag{5}$$

With the approximation that over a cross section the flow velocity is constant and equal to $\overline{v}(\ell)$, the variable kinetic energy of the system is expressed in the form:

$$K_v = M_p \left(\frac{ds}{dt}\right)^2 + \frac{\rho\alpha}{2} \frac{A_c^2 L}{A} \left(\frac{ds}{dt}\right)^2 \quad , \tag{6}$$

where L is the length of the test section and

$$\alpha \equiv \frac{A}{L} \int_s^{\ell_o + s_r} \frac{d\ell}{A(\ell)} \quad , \tag{7}$$

where the path of integration extends from the pistons to the free surface, with ℓ_o the total path length when $s = 0$. Since A_c and A_r, the values of $A(\ell)$ at the lower and upper limits of the integral, differ slightly, α depends slightly upon s. Differentiation with respect to s provides, with equation (3),

$$\frac{s}{\alpha} \frac{d\alpha}{ds} = \frac{\Delta\alpha}{\alpha} = \frac{s}{\alpha} \frac{A}{L} \left(\frac{A_c}{A_r} \frac{1}{A_r} - \frac{1}{A_c} \right) . \tag{8}$$

Then, by the dimensions of the tunnel, and since s cannot exceed S_m, $\Delta\alpha/\alpha$ cannot exceed 0.5 percent. Neglecting this small variability, the integral in equation (7) can be evaluated for $s = 0$, and α regarded as a constant.

The total energy E is the sum of the variable P_V and K_V plus an undetermined constant. Obtaining s^2 and $(ds/dt)^2$ from equation (2), using the identities:

$$\sin^2\sigma t \equiv \frac{1}{2}(1 - \cos 2\sigma t) \quad , \tag{9}$$

$$\cos^2\sigma t \equiv \frac{1}{2}(1 + \cos 2\sigma t) \quad , \tag{10}$$

and defining

$$\beta \equiv \frac{1}{2}\left(1 + \frac{A_c}{A_r}\right) , \tag{11}$$

the addition of equations (5) and (6) provides:

$$E = \left[M_a g y - \frac{\rho g \beta A_c S^2}{2} + \frac{1}{2}\left(\frac{\rho \alpha A_c^2\ L}{2A} + M_p \right) S^2 \sigma^2 \right] \cos 2\sigma t + \text{constant.} \tag{12}$$

Thus, the variation of E with time is proportional to cos $2\sigma t$, a simple form made possible by the prior choice of the rate of rotation of the active counterweight as twice σ, in anticipation of the identities in equations (9) and (10).

Equation (1) is then satisfied, and the power input is minimized if the coefficient of cos $2\sigma t$ in equation (12) is made to vanish, i.e., if the active counterweight is set to satisfy

$$M_a g y = \frac{\rho g \beta A_c S^2}{2} - \frac{1}{2}\left(\frac{\rho \alpha A_c^2\ L}{2A} + M_p \right) S^2 \sigma^2 \quad . \tag{13}$$

This expression is simplified by introducing y_m, the maximum y required when $\sigma = 0$ and when $S = S_m$, the maximum available amplitude, that is,

$$y_m \equiv \frac{\rho \beta A_c S_m^2}{2M_a} \tag{14}$$

and by introducing σ_o, the resonance frequency when $y = 0$, that is,

$$\sigma_o^2 \equiv \rho g \beta A_c \Big/ \left(\frac{\rho \alpha A_c^2 L}{2A} + M_p \right) \quad . \tag{15}$$

Equation (13) can then be written as

$$\frac{y}{y_m} = \frac{S^2}{S_m{}^2}\left(1 - \frac{T_o^2}{T^2} \right) , \tag{16}$$

where T_o/T has replaced σ/σ_o. y is positive or negative as T is greater or less than T_o.

In summary, for any given S and T, the tunnel operates at resonance when y is given by equation (16). The constants y_m, S_m, and T_o are determined by equations (7), (11), (14), and (15) and by the dimensions and masses of the components of the tunnel (see Table).

Table. Significant dimensions, masses, and constants of the water tunnel and drive system.

Quantity	Value	Symbol
Diameter of each cylinder	31.0 cm	
Combined area of cylinders	1509.6 cm^2	A_c
Maximum amplitude (half stroke) of pistons	50.0 cm	S_m
Depth of flow over sand bed	29.8 cm	A
Width of test section	20.8 cm	
Area of flow over sand bed	619.4 cm^2	A
Length of test section	252.9 cm	L
Diameter of each reservoir	30.1 cm	
Combined area of reservoirs	1423.2 cm^2	A_r
Depth of sand bed	25.8 cm	
Maximum displacement of active counterweight	43.4 cm	y_m
Mass of active counterweight	44.78 kg	M_a
Mass of both pistons and their yoke	71.24 kg	M_p
Resonance period with y = 0	5.31 s	T_o
Shape factor (eq. 7)	2.19	α
Shape factor (eq. 11)	1.03	β

Data describe facility in operating condition as of December 1976.

The volume of water displaced by a maximum stroke of the piston, $2S_mA_c$, is 151 liters. The corresponding linear displacement in the test section $2S_mA_c/A$, is 2.44 meters. The amplitude of the horizontal velocity is:

$$U = \frac{2\pi}{T} \left(\frac{A_c}{A}\right) S = \frac{765.7}{T} \left(\frac{S}{S_m}\right) \text{ cm/s} \quad . \tag{17}$$

IV. CONSTRUCTION DETAILS

1. General.

The tunnel is constructed primarily of steel, aluminum, and Lucite, with lesser amounts of polyvinyl chloride (PVC) and brass. Most of the standing framework is of 4.76- by 50.8-millimeter (3/16 by 2 inches) steel angle, with 4.76- by 63.5-millimeter (3/16 by 2 1/2 inches) angle used in the columns under the cylinders and reservoirs. Lucite members are regularly fused together with solvent. Removable sections are flanged and bolted together with gasket seals. The Lucite test section rests on a steel plate welded to steel angle stiffeners, but most metallic elements are bolted together. The aluminum cylinders are bolted to a 12.7 millimeter-thick (1/2 inch) aluminum slab; the reservoirs are of PVC pipe and glued to a 25.4-millimeter (1 inch) PVC slab base.

2. Cylinders, Pistons, and Seals.

Construction of the cylinders, a crucial element in the tunnel, was the most difficult. After failing in attempts to machine PVC pipe, and rejecting stainless steel pipe because of initial cost and reputation for difficult working, the cylinders were machined from aluminum pipe. Blemishes in the machining required hand-finishing, and variations in the cross-sectional areas were contained to less than 3 parts in 10,000. A final anodizing process to prevent corrosion roughened the surface slightly; however, subsequent tests revealed no undue friction or leakage between the cylinder walls and the piston seals. The cylinders are stiffened with flanges.

Each piston is machined from PVC, is 50.8 millimeters (2 inches) thick, and has two recessions, one each around its upper and lower perimeters. Rubber "U-ring" seals with cross sections like a square bottom letter "U" fit into the recessions. One horn of each ring presses against the piston and the other against the cylinder wall; horns of each ring face away from the other ring. The rings may need occasional replacement, but are inexpensive and readily available. The pistons have bleeds by which the space beneath them and between the seals can be kept free of air.

3. Components of the Drive System.

The apparatus is driven by a 3/4-horsepower Reeves variable-speed motor, by any one of three combinations of sprockets, a worm, and worm gear. The worm gear axis is a 31.8-millimeter (1 1/4 inches) steel rod. The two driving arms at opposite ends of the rod are made of 12.7- by 101.6-millimeter (1/2 by 4 inches) steel bar. Each arm has a sleeve which can be positioned by threaded rods at any distance, less than 50 centimeters from its axis. Each sleeve holds a ball-bearing pin which fits and slides in a 34.9-millimeter (1 3/8 inches) slot along the bottom of the adjacent triangular frame forming a side of the scotch yoke. As the two arms rotate about their axis, the yoke moves vertically in simple harmonic motion. The overall system is shown in Figures 1 and 2; details are shown in Figures 4 and 5.

The yoke is made of aluminum. The slot along the bottom of each triangular frame is formed by an aluminum bar spacer between aluminum angles lined with steel strips. The triangular frames are rigidly joined together at their upper corners, over the cylinders, by a bar made from two aluminum channels. Pins through these channels hold the upper ends of the connecting rods, made of aluminum tubing, which connect rigidly to the pistons below. The yoke is constrained to move vertically by upper and lower guides made of steel angle with spacers forming slots. The upper and lower corners of the triangular frames hold ball bearings which roll in the slots. The tops of the upper guides are fixed to a steel channel extending from wall to wall above the cylinders. The weight of the yoke and pistons is balanced by two steel (passive) counterweights supported by chains and overhead sprockets. The counterweights extend across the cylinders between the upper guides which also serve to steady them as they move.

The active counterweight (Fig. 5) is made of steel and held in position by threaded rods in a steel rectangular frame. This frame rotates about an axis over the motor, and is driven by chain and sprockets from the worm gear shaft at twice the worm gear shaft speed. A system of small sprockets, a chain, miter gears, and a crank permits the threaded rods to be turned, and the position of the counterweight adjusted, during operation. A scale mounted on the counterweight framework gives y/y_m (eq. 16).

A flywheel (Fig. 5) which rides on the drive shaft between the worm and the cylinder column is made from a pulley wheel with steel blocks bolted to its circumference. It weighs 20.4 kilograms and has an effective diameter of about 33 centimeters. A clutch permits the flywheel to be engaged or disengaged during operation.

The timing mechanism (Figs. 1 and 5) has several components. The end of a steel rod mounted traversely on the drive shaft just outside the cylinder column passes near a magnetic sensor during each rotation. An electronic timer, when activated, times and displays the interval

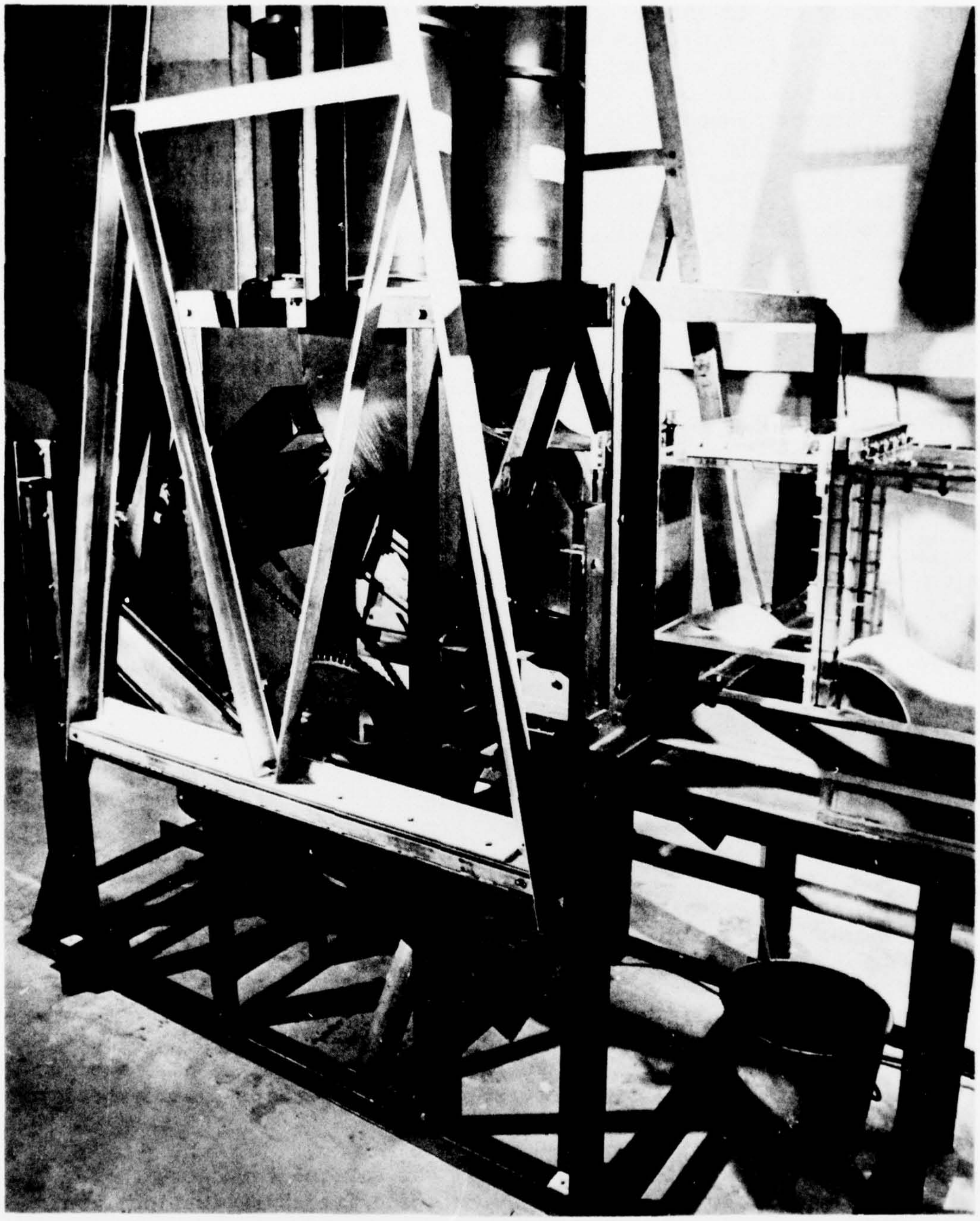

Figure 4. Photo of the drive system.

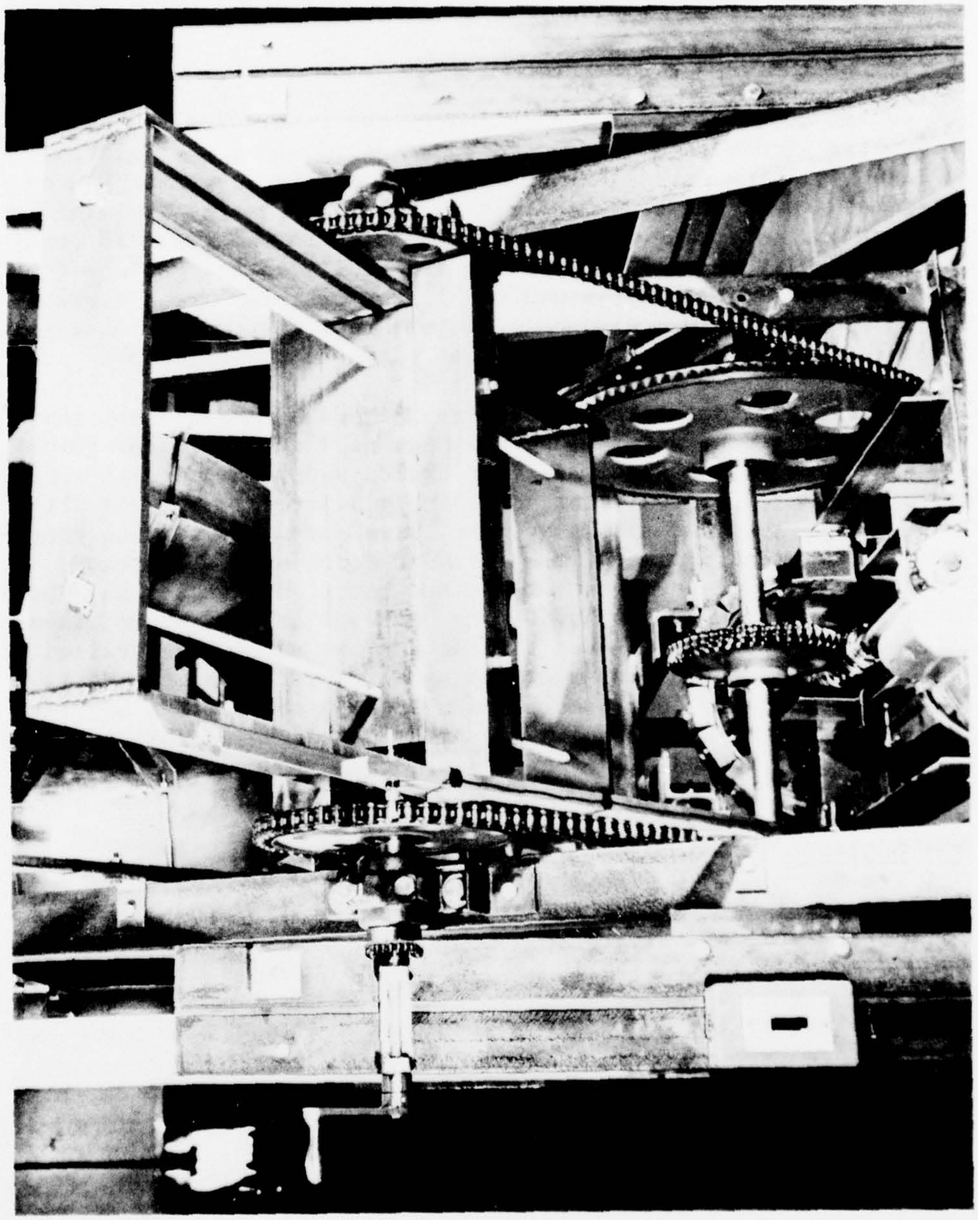

Figure 5. Photo of the active counterweight assembly.

between the succeeding two passes. The timer can be selectively activated whenever a contact on the rotating counterweight framework touches any of four equally spaced contacts along its circular path. Since the rate of rotation of the counterweight framework is twice that of the driving arms, a timing is possible every one-eighth cycle, or 45° of phase.

4. Connecting Conduits and Spools.

The curved conduits under the cylinders and reservoirs are of 1.0-millimeter (0.040 inch) brass sheet, soldered along the joints (Figs. 2 and 4). The cross-sectional area along the length of the conduits remains nearly constant, and a vane has been inserted to minimize flow separation. Just above the curved conduits in the lower 18 centimeters of the cylinders and reservoirs, are flow adapters between the rectangular cross section below and the larger circular cross section above. These adapters are also made of soldered, curved brass sections, and resemble large four-leaf clovers (not shown in the figures).

Each of the horizontal spools between the brass conduits and the test section is 41 centimeters long and made of 12.7-millimeter-thick (1/2 inch) Lucite. Each spool has been broken and rejoined with rubber tubing to form an expansion joint, containing a screen. Screens are also inserted between the spools and the curved conduits next to honeycomb flow straighteners placed just inside the conduits. To remove bubbles under the long level top of the test section, hatches have been cut in the tops of the spools and Lucite barriers erected around them. The hatch covers are removed when filling and the water level raised until about 2 or 3 centimeters over the spool top, filling the test section and flooding the enclosed areas over the spools. The bubbles can then be swept out by pulling a buoyant sponge from one hatch to the other at the opposite end. The hatches are then secured, the flooded areas drained, and the filling continues.

5. Test Section.

The test section is a Lucite tank with 19.1-millimeter-thick (3/4 inch) walls and ends and with a 25.4-millimeter-thick (1 inch) top (internal dimensions are given in the Table). The walls are stiffened externally by a pair of steel channels extending the length of the tank and held together by tie rods through the tank and under the surface of the sand bed.

6. Permeability Study Configuration.

In the permeability experiments, performed before the tunnel was modified, the mean depth of flow over the sand bed was usually 16.6 centimeters, about half the present value (Lofquist, 1975). The test section was divided longitudinally into two channels connected only by a gap extending along the bottom of the test section beneath the sand. A pair of plungers in the reservoirs oscillated vertically and oppositely,

driven off an extension of the worm drive shaft by two separate scotch yokes similar to but smaller than that previously described. The action of the plungers caused a sinusoidal pressure difference between the two channels and an oscillatory permeability flow into and out of the sand bed surfaces and through the connecting gap below.

7. Durability.

The materials in the apparatus which are in contact with water (Lucite, anodized aluminum, brass, PVC) are noncorrosive in that element. During modification of the tunnel, spots of a scaly deposit were found on the inner walls of the cylinders, and were removed by brushing. These spots may have been calcium deposited during a time before distilled water was used. Lucite immersed in water for long periods will expand, with an ultimate extension in length of about 0.33 percent. Allowance for this expansion was made in the construction. No parts of the apparatus are subject to significant wear except the piston seals which can be replaced.

V. OPERATIONAL SEQUENCE

A typical sequence of operation of the water tunnel follows. It is assumed that the sand is already in the tank, the system filled with water, and the bubbles removed as described in Section IV, 4. The flywheel is disengaged, and the motor is turned off. The pistons have been bled and covered with a shallow layer of water to ensure that the seals are always completely wet. The sequence then continues:

(a) The driving arms are moved into horizontal position by manually turning the drive shaft, since only when the arms are parallel to the slots in the yokes can the sleeves holding the bearing pins be freely moved.

(b) The amplitude S is then set on the driving arms.

(c) The motor is then turned on and the speed gradually increased until the period is reduced to its operating value, T.

(d) If S/S_m is considerable, e.g., greater than 0.3, y/y_m is adjusted in increments during speedup, according to equation (16). Otherwise, y/y_m can be set when steady operation is attained.

(e) The flywheel turning freely on the drive shaft is then engaged.

At the end of the experiment, the flywheel is disconnected, the speed of the motor is reduced while adjusting y/y_m in increments if necessary. When the motor is at low speed it is turned off.

VI. PERFORMANCE

The tunnel has operated over wide ranges of amplitude and period in a special series of tests and in the completed permeability experiments (Lofquist, 1975). The special tests investigated the constancy of the rate of rotation of the driving arms throughout a cycle and the leakage past the piston seals. In these tests, made before the tunnel was modified, the depth of flow in the test section was only 15.6 centimeters and the amplitude of the horizontal velocity was given by

$$U = \frac{1505}{T}\left(\frac{S}{S_m}\right) \mathrm{cm/s}$$

rather than by equation (17). These tests extended to values of U able to sweep away sand and were performed with wooden boards in place of a sand bed surface. Also, no screens were mounted in the spools.

The tests for constancy of speed were made with the electronic timing apparatus in the ranges: S/S_m between 0.095 and 0.64, T between 3.0 and 25 seconds, and U between 30 and 150 centimeters per second. Generally, variations in speed from average values increased with U, but all variations were small. For U less than 50 centimeters per second, the variations remained less than ± 0.25 percent; for U less than 100 centimeters per second, less than ± 0.5 percent. The largest observed variation, at $U \approx 150$ centimeters per second, was around ± 0.8 percent. The smallness of these variations shows that the steepness of the motor torque-speed curve, the inertia of the system, and the active counterweight combine to offset the effects of friction in the flow and between cylinders and pistons. For given S/S_m and T, variations in speed were observed to increase as the active counterweight was moved from its proper position given by equation (16).

Ideally, a constant rate of rotation of the driving arms would ensure pure simple harmonic motion of the pistons. However, the elasticity of the scotch yoke and the clearance between the ball-bearing pins and the scotch yoke slots permit the friction between the piston seals and the cylinder walls to hold the pistons at rest for a finite time interval, δt, at their extreme upper and lower positions. This interval persists while the pins move through some small vertical distance and the driving arms turn through some small angle equal to $2\pi\ \delta t/T$, so that $\delta t/T$ increases as S/S_m is reduced. At small strokes this effect can be detected as a slight jerk in the flow just following flow reversal.

An average rate of leakage past the piston seals was obtained by measuring the changes in depth of shallow layers of water over the pistons after an operation of around 100 cycles. No attempt was made to determine the instantaneous rate of leakage as function of phase. The changes in depth were hard to detect, and did not exceed a few tenths of a millimeter. This represents a volume leakage per half cycle of not

more than about one part in 100,000 of the volume displaced by the pistons. The tests were performed for S/S_m = 0.33 and 0.64, and in the ranges, T between 3 and 25 seconds and U between 30 and 150 centimeters per second.

In the permeability experiments (Lofquist, 1975) the tunnel provided flows over naturally rippled sand with a mean diameter of 0.56 millimeter. Values of S/S_m remained small, about 0.07, 0.10, and 0.14 (each corresponding to a different ripple size); T ranged from 3 to 14 seconds. Values of U were kept below about 35 centimeters per second to prevent excessive sand motion and erosion of the ripple profiles. During the 50 experiments, each lasting about 6 hours, the tunnel performed without serious incident.

VII. CONCLUSION

The tunnel described in this study may be compared with four other oscillatory water tunnels that have been built. Two tunnels are of vertical U-tube design and use pneumatic devices to maintain the oscillatory flow. The first tunnel, described by Carstens and Neilson (1967), operates only at a resonance period of about 3.6 seconds where it maintains a nearly sinusoidal flow. The second tunnel, described by Lundgren and Sorenson (1957), can operate over a wide range of periods above 3 seconds; however, it is unclear how nearly sinusoidal its basic flow remains at periods removed from a resonance period of 9 seconds.

The other two tunnels are of a horizontal closed-loop design, and operate by the nearly positive displacement of a close-fitting (though not tight) piston in one side of the loop. In one tunnel, described by Dedow (1966), an electronically controlled hydraulic drive can provide almost any specified flow-time relationship. In the other tunnel, described by Brebner and Riedel (1973), a motor drive operating over a wide range of periods provides motion as nearly simple harmonic as is compatible with an eccentric and connecting rod.

The test cross sections of all four tunnels exceed that of the present tunnel, and the two horizontal closed-loop tunnels are massive installations. Thus, aside from its unique capabilities for the permeability study (the paired pistons and reservoirs; Lofquist, 1975), the tunnel described in this study has no single capability not found or exceeded in the other tunnels. However, the present tunnel requires very little power (3/4 horsepower, as compared to the 25-horsepower motor of the closed-loop tunnel described by Brebner and Riedel, 1973), and yet is able to provide a sinusoidal flow over wide ranges of period and amplitude. Thus, the present tunnel may be regarded as a proven design compatible with limited space and resources.

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